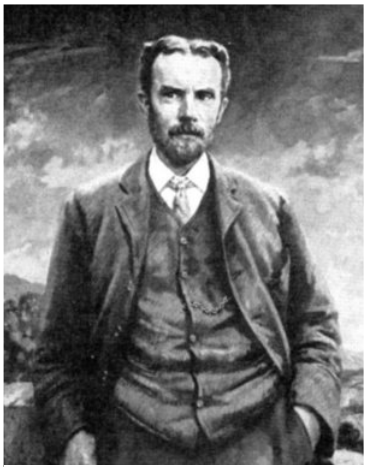
Oliver Heaviside -- a first rate oddity -- sage in solitude

John S. Belrose, PhD Cantab
Technical Editor Proceedings of The Radio Club of America



Oliver Heaviside (1850-1925)

Preface

The very possibility of wireless communications are founded on the work of James Clerk Maxwell, whose name is synonymous with electromagnetic waves and the basis of wireless. But not realized by many is that the four equations that we use today under the heading “Maxwell’s Equations” were written by Oliver Heaviside, who put them in vector form. Maxwell’s Equations (of which there were many more than four, some 20) were written in terms of several different variables, fields and potentials, as well as current density, and they were in Cartesian Format, with each component stated separately. Heaviside was convinced that the formulation should be in terms of fields (E and H) rather than potentials and in general the vector rotation which makes the symmetry and excellence of the equations so clear. Every engineer is aware of Maxwell’s equations, the four mathematical expressions, that explain the full behavior of electromagnetism ---and grace many engineering school sweatshirt!!

Introduction

When I began my studies on antennas and propagation, at the University of British Columbia, the course work for my Masters Degree (1950-1953) was based on two publications/text books, Oliver Heaviside [1], and Edward C. Jordan [2]. And a third book, by S.K. Mitra [3], became my bible, self selected, since studies for my thesis were concerned with a study of the E-region of the ionosphere.

I never really understood Heaviside’s operational calculus, and I did not in that time period realize a connection between Heaviside and Maxwell. Jordan’s book made no mention to Heaviside. And, since I have not tried to improve my understanding since, my lack of understanding on what Heaviside did has always been in the back of mind, until recently. In November 2012, I found a paper by Bruce Hunt [4] on Oliver Heaviside. The subject of this paper is prompted by what Hunt wrote, and as well on my extensive background on antennas and propagation. I begin (see below) by a direct quote from Hunt’s first paragraph (hence quotation marks).

Heaviside’s development of his operational calculus in 1884 for solving electromagnetic problems was largely empirical, and lacking in mathematical rigor. His operational method was placed on a sound mathematical basis by many many men, beginning in 1916 by T. Bromwich and K.W. Wagner; and by Van der Pol, 1929; Poisson and Laplace transformation, c1950; and an understanding of Heaviside’s operational calculus and electromagnetic theorems continues today; for example Paul Nahin in 2001 [5]; Hugh Griffiths in 2006 [6]; and Bruce J. Hunt (above reference).

Following Maxwell

"When physicists today write down Maxwell's equations in their standard vector form or simply set up a problem using vector analysis, *they are drawing, usually without realizing it, on the work of Oliver Heaviside.* When they analyze how electromagnetic waves move along a wire or across space, or when they use such words as "impedance" or "inductance," they are following in Heaviside's footsteps. And when at the climax of the musical *Cats*, they are alluding to the chorus members sing about how Grizabella is about to rise ***"Up, up, up past the Russell Hotel / Up, up, up, up to the Heaviside Layer"***, alluding to Heaviside's idea that there must be a conducting layer in the upper atmosphere—though few in the audience probably catch the reference."

"Oliver Heaviside (1850–1925) was a self-educated English mathematical physicist who spent most of his life on the far fringes of the scientific community. Yet he did more than anyone else to shape how James Clerk Maxwell's electromagnetic theory was understood and applied in the 50 years after Maxwell's death. Indeed, Maxwell's equations in their most familiar vector form come from Heaviside".

Heaviside first read Maxwell's "Treatise" shortly after it came out in 1873. He said later he did not understand Maxwell's theory until he rewrote it. Heaviside made his greatest advance in 1884, while exploring how energy moves through the electromagnetic field. Maxwell had given formulas based on the electric and magnetic fields E and H for how energy is distributed in the field, but he never explained how it got from one place to another. In a series of papers published between 1874 and 1881, in Philosophical Magazine, and The Journal of the Society of Telegraph Engineers, Heaviside had extended William Thomson, later Lord Kelvin's theories on transmission of telegraphic transmission on long wire cables, to take into account current leakage and self induction.

Heaviside in 1884 dug into the equations in *Maxwell's Treatise* to find out how energy moved. After laborious transformations, Heaviside extracted a remarkable simple result, the flow of energy at a point on a wire or in space is simply the vector product of the electric and magnetic fields there (ExH).

We read that Heaviside said that "the real action lay ***not within conductors*** but in the field around them. Engineers have found the statement italic bold difficult to accept, since after all the fields around the conductors are generated by the current on the conductors. Jordan, reference [2], discusses this issue in some considerable detail --- difficult to understand and accept. But one must remember that when Heaviside made this statement he was concerned with transmission lines. In my interest, antennas and propagation, one generally ignores radiation by transmission lines, excepting for special cases, a coaxial cable feeding a balanced dipole antenna without an balanced-to-unbalanced transformer (a balun). But, the interpretation of ExH as the power flow per unit area is an extremely useful concept, especially in radiation problems. For example, an integration of ExH over a surface enclosing a transmitting antenna gives the power radiated by the antenna.

Heaviside did not have much access to scientific journals, and so he did not learn until late in 1885 that Cambridge trained physicist John Henry Poynting had hit upon the same energy flow theorem shortly before him. The Royal Society published an abstract of Poynting's result in January 1884, and the full paper later that year. Not withstanding Heaviside continued his studies, deriving his four basic equations, which we nowadays call "Maxwell's Equations", usually with no reference to Heaviside. And Heaviside's energy flow vector equation is referenced to Poynting rather than Heaviside.

Continuing, and concluding this section, on the concept that the real action was not due to current on wires was due to the field around them. Though certainly shared by Heaviside, was stated more directly by the Irish physicist George Francis FitzGerald in an exchange of letters in the magazine "Nature" in 1885. FitzGerald objected with what he thought was a misunderstanding of Maxwell's theory on the part of Sir William Thomson (later Lord Kelvin). FitzGerald and Heaviside struck up correspondence late in 1888, and though they only met in person twice, they became good friends through their letters --- until 1901, the date of FitzGerald's early death. Heaviside later said that FitzGerald's views on Maxwell's theory were very close to his own.

The real action lay not within the conductors but in the field around them

The words in the title of this section are the words that caught my attention, and the words that prompted what I am writing. The antenna system which I am about to describe is the best example, in my view, to support what Heaviside said, about 130 years ago. A topic that has interested me for many years is the flow of current on wires (transmission lines, and antennas). Let me tell you what I have written about am umbrella top loaded antenna systems, a vertical tower with active sloping wires connected to or insulated from the top of the tower --- an interesting antenna system analysis (using EZNEC4 High Precision --- after Roy Lewallen), very relevant here.

Vertical radiators that are electrically short have a low radiation resistance and a relatively high capacitive reactance. For this type of antenna to take power, the capacitive reactance must be tuned out by a suitable inductor, and the resistive component of the antenna's impedance matched to the characteristic impedance of the transmission line feeding the antenna. This tuning inductor introduces an additional loss resistance, and the object of design is to obtain the highest possible practical ratio of radiation resistance (R_r) to total resistance of the antenna system (R_{as}), which includes ground induced loss.

It is clear that some form of top loading should be used to increase the capacitance of the antenna and so reduce the capacitive reactance at the base of the antenna, and to increase the current area on the vertical radiator, and so increase the radiation resistance.

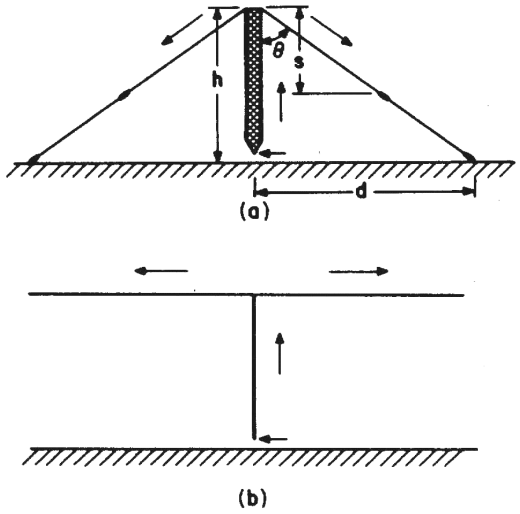


Figure 1 Sketches illustrating phasing of currents on a) umbrella antenna; and b) a T-type antenna.

The umbrella antenna is one method to top-load a tower, without the need to install additional towers to support the top-loading. This antenna type is illustrated in **Fig. 1a**. The top loading consists of a number of active umbrella wires, connected to the top of the tower, and strung obliquely to ground. The important parameters for such an antenna are the height, h, of the tower; the horizontal distance, d, from the base of the tower to the extremities of the insulated guys supporting the conducting umbrella wires; and the vertical distance, s, from the top of the tower to the height where the umbrella wires are broken by an insulator.

The sketches in **Fig. 1** also illustrate the phasing of the currents on the umbrella antenna, compared with (for example) the T-type antenna. In the case of the T- type, the currents on the flat top and on the vertical part of the antenna system are not opposing, since the currents on these elements are orthogonally oriented (in space). Also, recall, considering the antenna and its image in the ground, that only the currents on vertical parts of the antenna contribute appreciably to radiation. The currents on the flat top and on the image of the flat top in the ground are in phase opposition, and so essentially cancel insofar as radiation is concerned. The currents on the vertical parts of the radiator and their image in the ground are in phase.

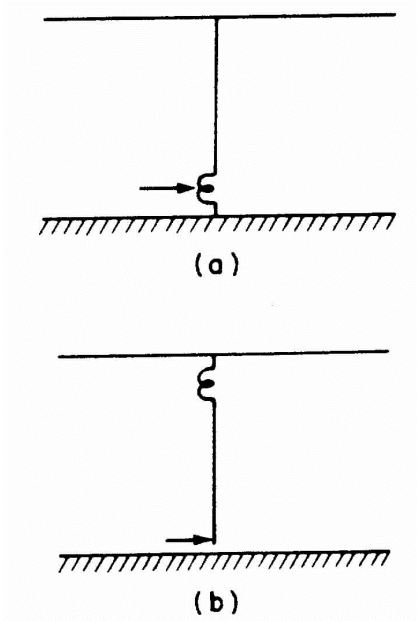


Figure 2 Sketch shown in a) a base tuned T-type antenna; and in b) tuning at the top of the tower.

The sketches in **Fig. 2** illustrate a simple T-antenna (what follows also applies to the umbrella antenna), employing two methods of tuning the antenna. In **(a)**, the method that is commonly used, an inductor which has a reactance equal to the capacitive reactance of the antenna is used to resonate the antenna. The sketch in **(b)** illustrates an antenna type that is seldom used because of the electrical and mechanical difficulty in installing and adjusting a coil at the top of the tower, and servicing it if damaged by lightning. If this inductor is tunable, it can be adjusted so that the base reactance of the antenna system is zero, and the radiation resistance is a maximum. This is because the current area on the tower is a maximum. The improvement in radiation efficiency is, however, partly compromised by the fact that a larger tuning inductance must be used, compared with the conventional base-loaded radiator. However, Smith [7] has devised a method to overcome this limitation (see below).

Smith, in the reference cited above, describes an electrically short umbrella antenna system which employs a tuned elevated electrically short radial wire ground system (see **Fig. 3)**. This is an interesting antenna, not only, from the author's point of view, because of his interest in insulated Elevated radials [9, 10] but, notice the

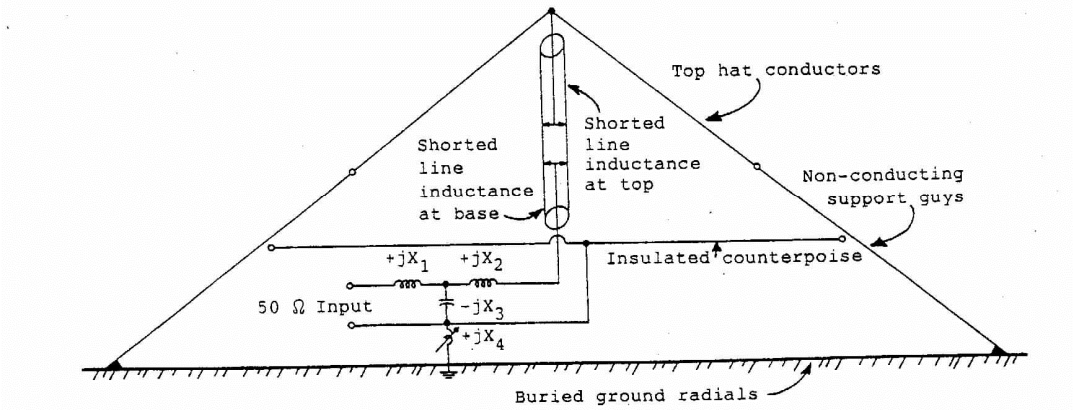


Figure 3 Umbrella top-loaded monopole antenna with electrically insulated radial wire counterpoise (after Smith [7]).

way in which Smith has configured the tower. A low loss inductance at the top of the tower is achieved by insulating a suitable conductor inside the tower and shorting it to the tower at some judicious length away from the end. This arrangement forms a coaxial line with one end open and the other end short circuited. The inner

conductor of this shorted coaxial line is connected to the top hat conductors. This is rather clever -- the author had previously not seen such an arrangement.

Note: more series inductance at the bottom of the tower can be added by insulating a conductor up inside the tower to a shorting point --- but for an electrically short antenna the author has placed inductance only at the top of the tower. A low loss base loading coil is used to resonate the antenna system.

The current distribution on the top hat conductors can be assumed to be sinusoidal, with zero current at the outer ends and a maximum current at the top of the tower where they are joined together. At this point the top loading inductance in series can replace an appreciable portion of the sine wave, with the result that the current distribution on the tower can be essentially constant.

In Figure 3 I show as noted above is a copy of the antenna system Smith described. The tower is shown is a cylinder. The antenna system I analyzed [8] was a more realistic model, see Figure 4, viz. a lattice tower with an elevated radial wire ground system (radial height 2 m), references [8, 9, 10]. The number of radials for a 4-sided tower, for the configuration modeled, has to be a multiple of four, 4, 8, or 16 radial wires (see below).

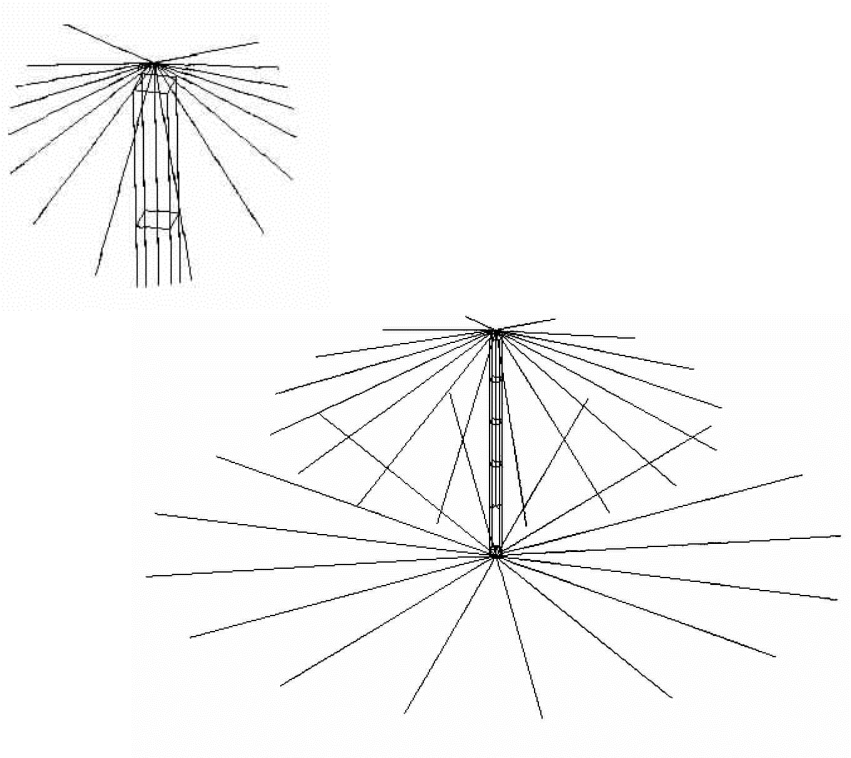


Figure 4 Wire model for one of the antenna systems analyzed

Smith describes his view with respect to minimizing ground loss. The E-field between the top hat and the counterpoise can be likened to a transmission line that is open at one end and shorted at the other. There is an E-field between the top hat and the counterpoise, and some of the E-field passes through to the ground beneath. The counterpoise potential is maintained so as to minimize the current in the lossy ground. The author had previously noted that for an umbrella type antenna with elevated radials, one radial wire should be so arranged that it lies directly under the overhead umbrella wire.

For the antenna system under discussion, the sloping umbrella wires are insulated from the top of the tower, and are connected to a wire that runs down the centre of the lattice tower. This wire is fed by a current source connecting to the tower at some point or at the bottom of the grounded tower. Employing a modern antenna system modeling program, based on a program called NEC (numerical electromagnetic code), one can correctly predict the performance of this antenna system --- I have, reference [8], computed the radiation characteristics

for station KVOK's antenna for comparison with the measured data reported by Smith. NEC-4D did in indeed model this antenna system quite effectively.

And surprisingly the top part of the lattice tower carries currents that flow on the inside surface of the tower, and on the outside surface of the lattice tower. The electromagnetic fields due to currents that flow on the inside of the tower are transmission line currents; and the currents that flow on the outside surface of the tower, are radiating currents. Clearly as Heaviside concluded 130 years ago, the real action of current source on wires of a conductor is due to fields that surround it! That NEC can correctly predict the performance of this antenna system was, for me, amazing.

The NEC program that I use has been developed by many electromagnetic engineers, Gerry Burke; Edward Miller; and for practical numerical modeling of antennas, Roy Lewallen; and many others. Heaviside would certainly been very pleased to read what one can do with modern antennas system analysis programs, and to see that one can in fact analyze antenna models that result in current flow on the inside and outside surfaces of lattice towers.

Concluding Remarks

Heaviside was a "self made-man", deprived of regular study at university or engineering college. Nevertheless, his curious results and techniques, created by himself, led to results and techniques and theoretical physics that are undoubtedly the most important ever reached. I was particularly interested to read what Griffiths has written: "It is likely that Heaviside's insight and his unusual creative approaches to solving problems were his lack of a university education; there is perhaps a lesson for those of us who teach university courses, and we may ask, if another Heaviside were to appear, how the scientific establishment would recognize and treat him or her". Heaviside's insight and creative approaches were "due to" or "rooted in" his lack of a university education. His work was ultimately recognized, and his legacy to us today is certainly significant, not the least by way of the Heaviside step function and the Heaviside Layer.

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Acknowledgement

I am pleased to say that Bruce Hunt read my draft manuscript and he provided brief comment. In particular he referenced his book "The Maxwellians" (Ithaca, NY, Cornell University Press, 1991; reissued 2005). There is much more about Heaviside's physics and mathematics, and especially about his involvement in the 1880s and 1890s with other proponents of Maxwell's electromagnetic theory (principally G.F. FitzGerald, Oliver Lodge, and Heinrich Hertz).

Addendum

I had been thinking about writing what I have written for some time. The referenced article (and earlier writings) by Bruce J. Hunt, prompted my up dating what I had drafted; and, ***the "Did you know? ---"*** posting by Michael Geselowitz (see below) prompted finalizing my manuscript and publishing it.

The IEEE has recently told us ***"The truth behind those well-known (Maxwell's) formulas"*** (reference: the institute.ieee.org/technology-focus/technology-history/did-you-know-someone-else-wrote-maxwells-equations), an article written by Michael Geselowitz, 20 May 2013. Michael Geselowotz is the Senior Director IEEE History Center. The reference article is another in the series of "Did you know?" articles that uncover interesting historical, technical, and IEEE-related factoids. For those interested GOOGLE will find for you the reference article.

And, continuing, before concluding, I have just received my copy the University of Cambridge **CavMag** – **News from the Cavendish Laboratory**, July 2013, which prompted my corresponding with Professor Malcolm Longair, Editor of the CavMag Magazine. I sent him copy of my draft article. He replied: "Of course, it is very well known that Maxwell started with many more than the standard four equations". And, he brought my attention to the Autumn 2012 **newsletter**, published by The James Clerk Maxwell Foundation, article by John Arthur and David Forfar, entitled ***"The Changing Notation of Maxwell's Equations".*** These authors wrote: "In 1887, Hertz (1857-94) demonstrated electromagnetic signals being transmitted across his laboratory, they traveled at finite speed, were reflected from (conducting) surfaces and caused interference patterns, just like light waves. This vindicated experimentally Faraday's and Maxwell's unique insights, and today the achievements of Faraday and Maxwell stand amongst the greatest in physics. Unfortunately Faraday and Maxwell did not live to share in the triumph that resulted in Hertz's discovery. Hertz went on, in 1890, to publish a clarification of Maxwell's equations. Although they were mathematically equivalent to Heaviside's version, Hertz did not adopt the new vector notation and simply wrote out his equations the long way."

One can read further, in the referenced article, that Einstein once said "I stood on the shoulders of Maxwell --- ". Indeed one of the cornerstones of Einstein's 1905 paper on his special relativity is that measurement made by observers with different uniform velocities are related by Lorentz transformation. Not only do Maxwell's equations lead to the same conclusions, they are fully compatible with Einstein's special relativity, just as they stand.

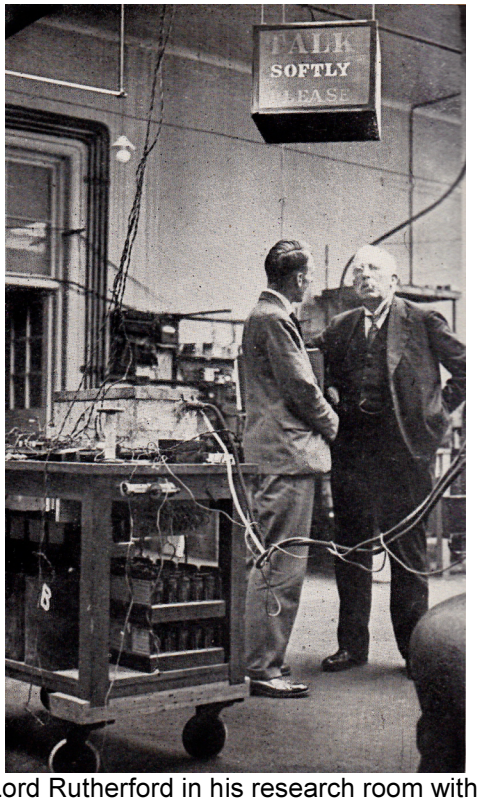
The efforts of Heaviside, Helmholtz and Hertz all contributed to the simplification of the equations. Heaviside critized Helmholtz, because Helmholtz'e electromagnetic theory allowed for the existence of longitudinal rather than solely transverse wave propagation. In 1880 Hertz obtained his PhD from the University of Berlin, and remained there for post-doctoral research under Helmholtz. In 1885 Hertz became a full professor at Karlsruhe, University where he researched electromagnetic wave propagation. Hertz died very young, age 36 years, on 1 January 1894.

Afterword: In March 1871 James Clerk Maxwell (1831-1879) was elected to the Chair (the first Chair) of the Cavendish Laboratory, which was to be housed in a building yet to be built. The building was available for partial occupancy in the Michaelmas Term in 1873. Maxwell's duties were described as being to "teach and illustrate the laws of Heat, Electricity and Magnetism; and to promote his study in the University (reference ***"The Cavendish Laboratory",*** Alexander Wood, Cambridge University Press, 1946). The Laboratory was then

situated on Free School, as it was when I was there, in 1953-1956. The Laboratory has changed significantly since then, in location, size, research program and capability to conduct research.

Two figures from the referenced booklet are reproduced: James Clerk Maxwell; and one that I like, J.A., Jack, Ratcliffe (1902-1987) in the research room of Lord Rutherford, in about 1936. (Rutherford died suddenly in 1939). Ratcliffe was my mentor, and the in-house examiner of my thesis for a PhD. The sign above Rutherford reads: “Talk Softly Please”, because the detectors used were very sensitive to vibration and noise. Rutherford, whose deep booming voice disturbed the detectors more than anyone else, didn’t seem to think the warning applied to him, was in loud conversation when the photograph was taken.

James Clerk Maxwell
(13 June 1831-5 Nov 1879)



Lord Rutherford in his research room with J.A. Ratcliffe

A major step forward in the current development of The Cavendish Laboratory is the award of a substantial grant from the UK Higher Educational Funding Council for England (HEFCE). for the construction of a new building, to be called ***The Maxwell Centre***, to be completed in late 2015. Maxwell is indeed importantly honoured. This announcement was made on 6th June 2013 (see previous reference to the July 2013 issue of CavMag).

John S; Belrose, PhD Cantab, Alumni The Cavendish Laboratory (1953-1958), Technical Editor The Proceedings of the Radio Club of America.